The role of sea ice in atmosphere-ocean energy and momentum transfer

Insights from remote sensing

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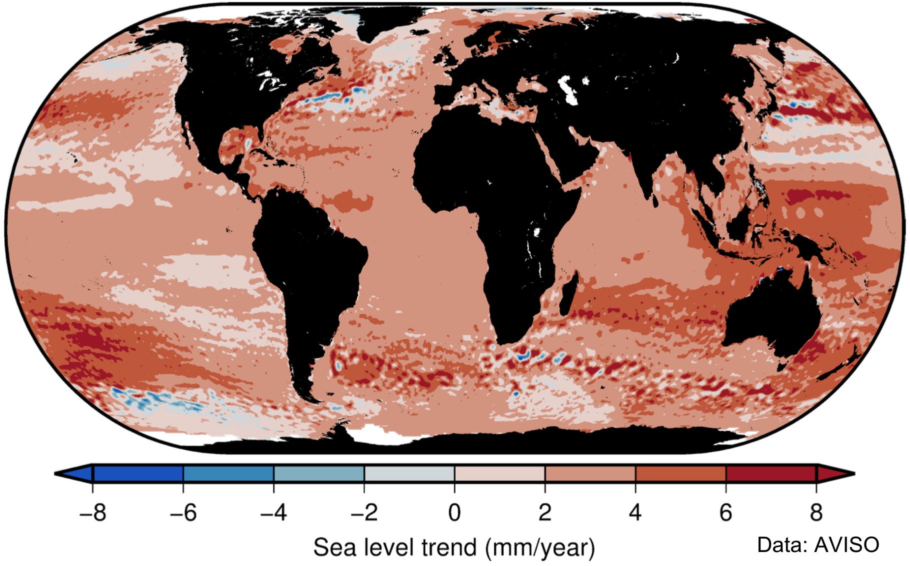
Outline

1. Background
2. Surface stresses
3. Atmosphere–ice–ocean *momentum* transfer
4. Atmosphere–ice–ocean *energy* transfer
5. Eddy–ice interactions

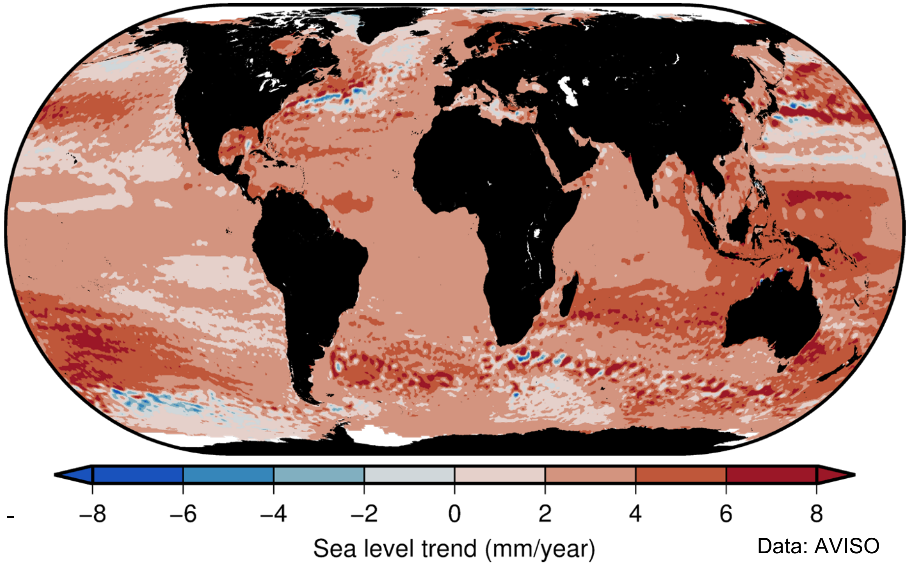
1. Background

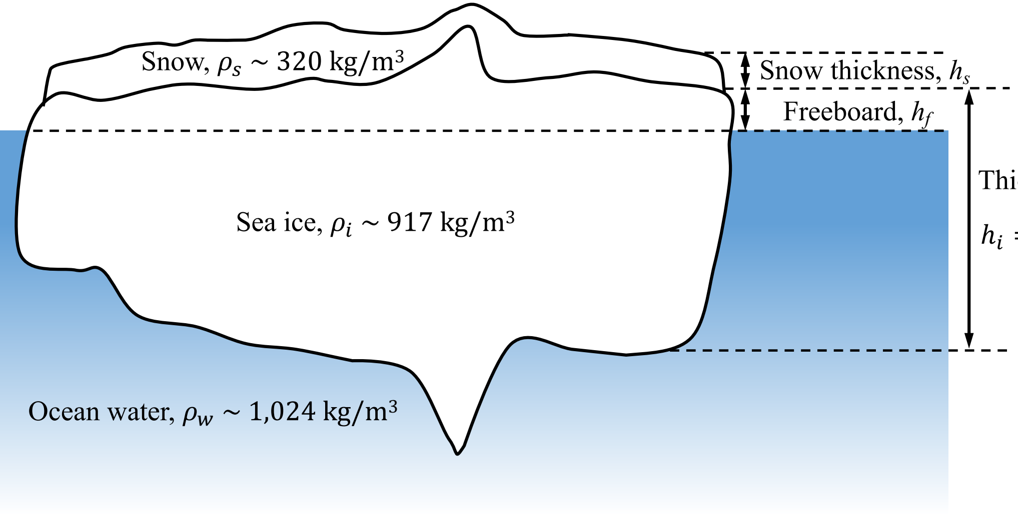
- Satellite radar altimetry
  - Measures sea surface height over the global (wet) ocean



1. Background

- Satellite radar altimetry
  - Measures sea surface height over the global (wet) ocean
  - Can estimate sea ice thickness





Thickness:

$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i}\right) h_f + \left(\frac{\rho_s}{\rho_w - \rho_i}\right) h_s$$

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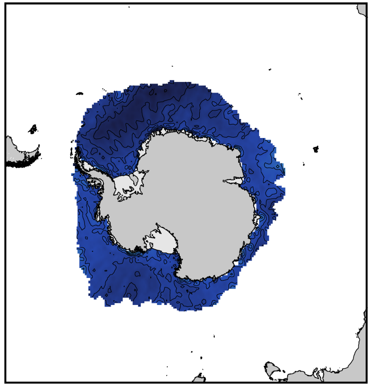

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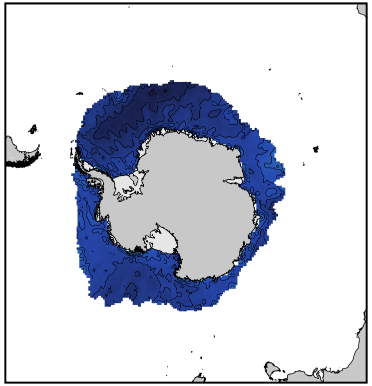

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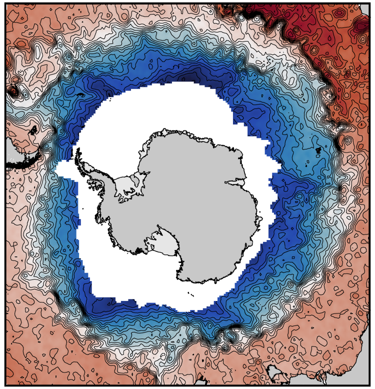

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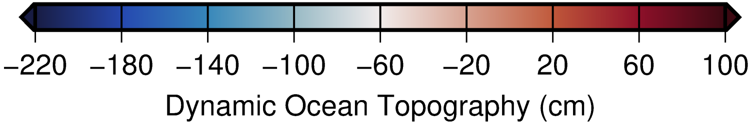

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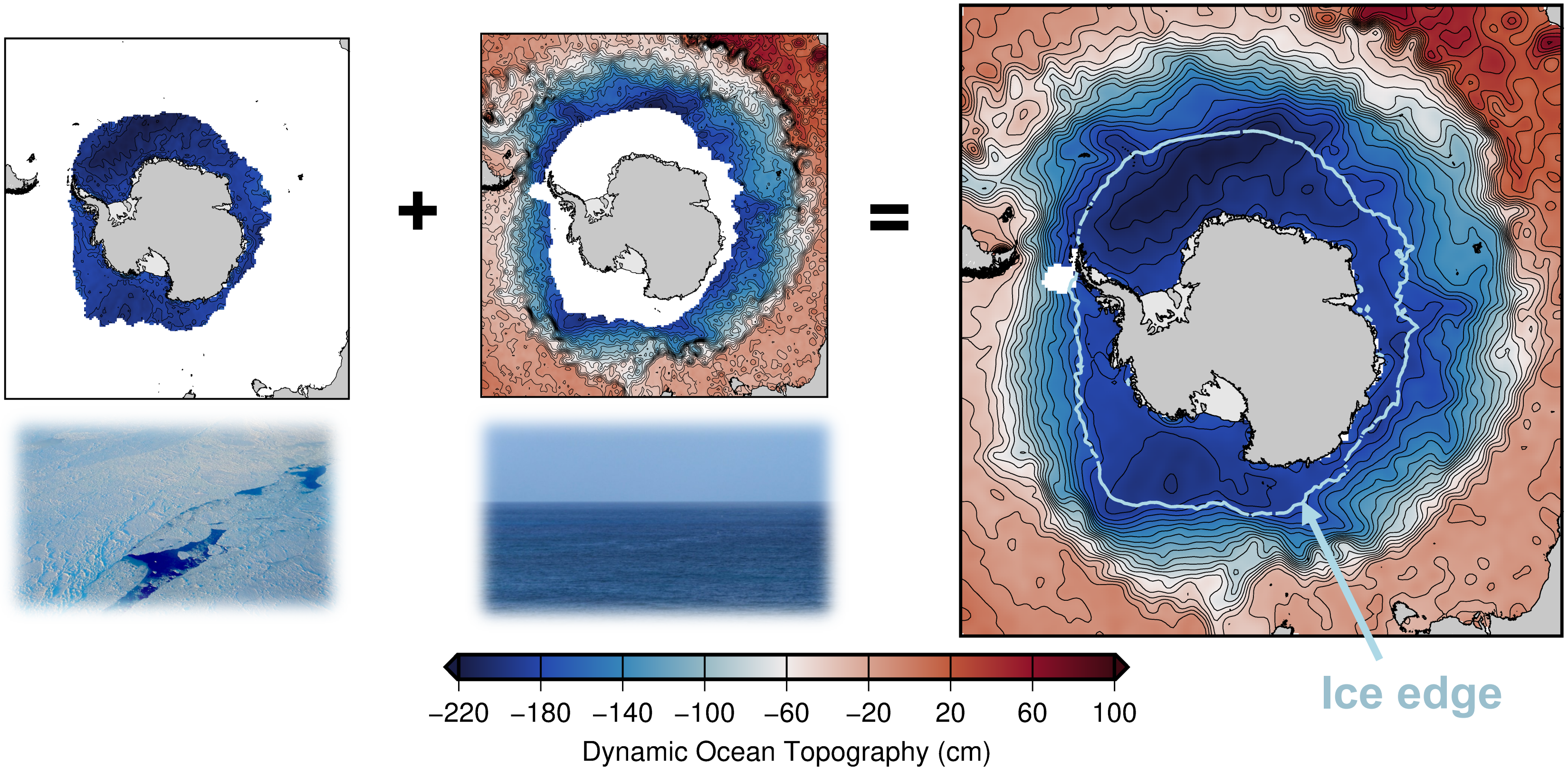

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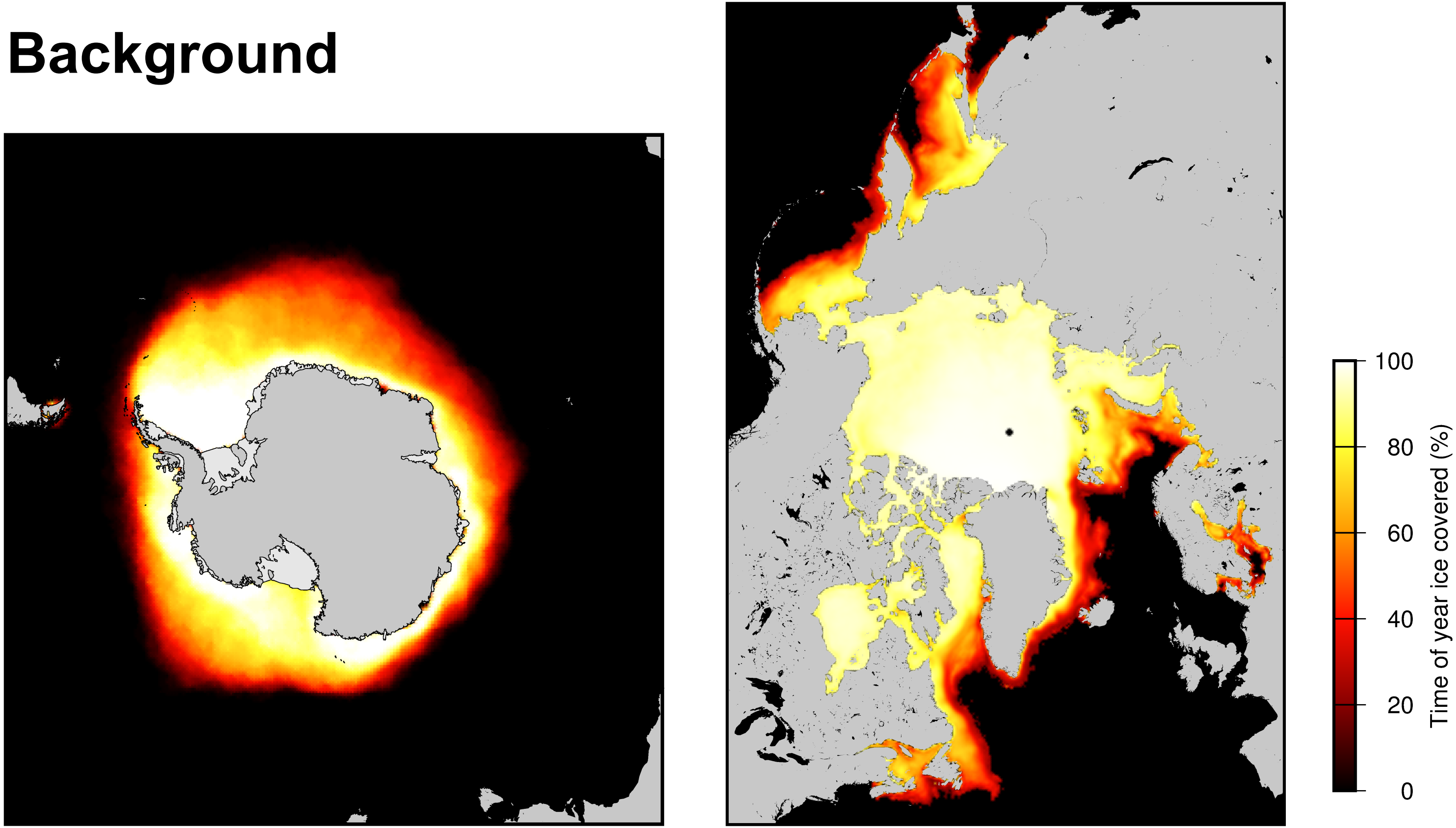

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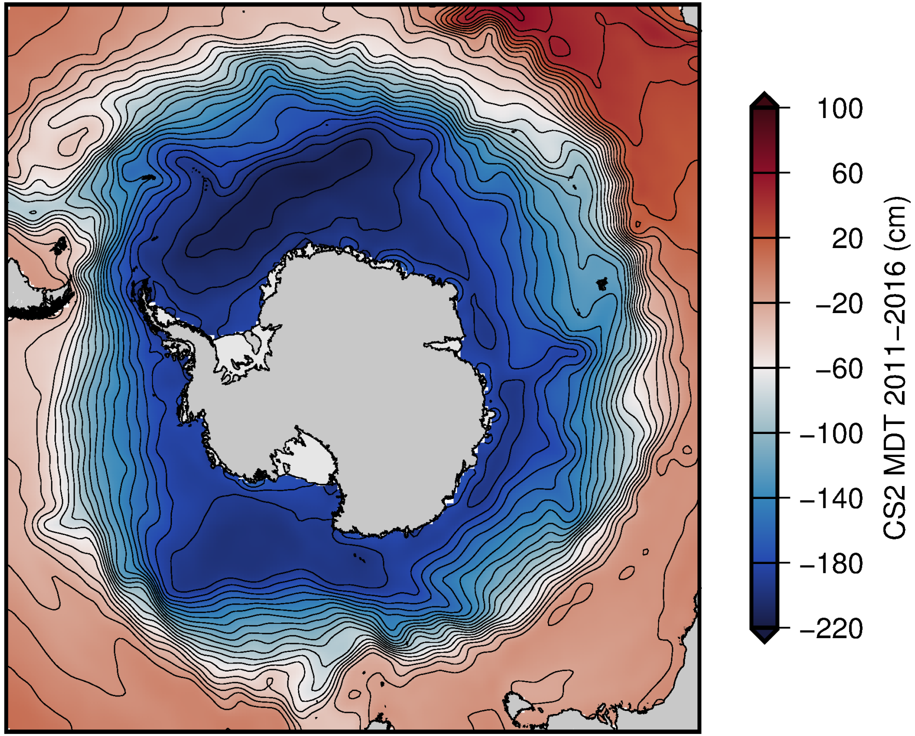

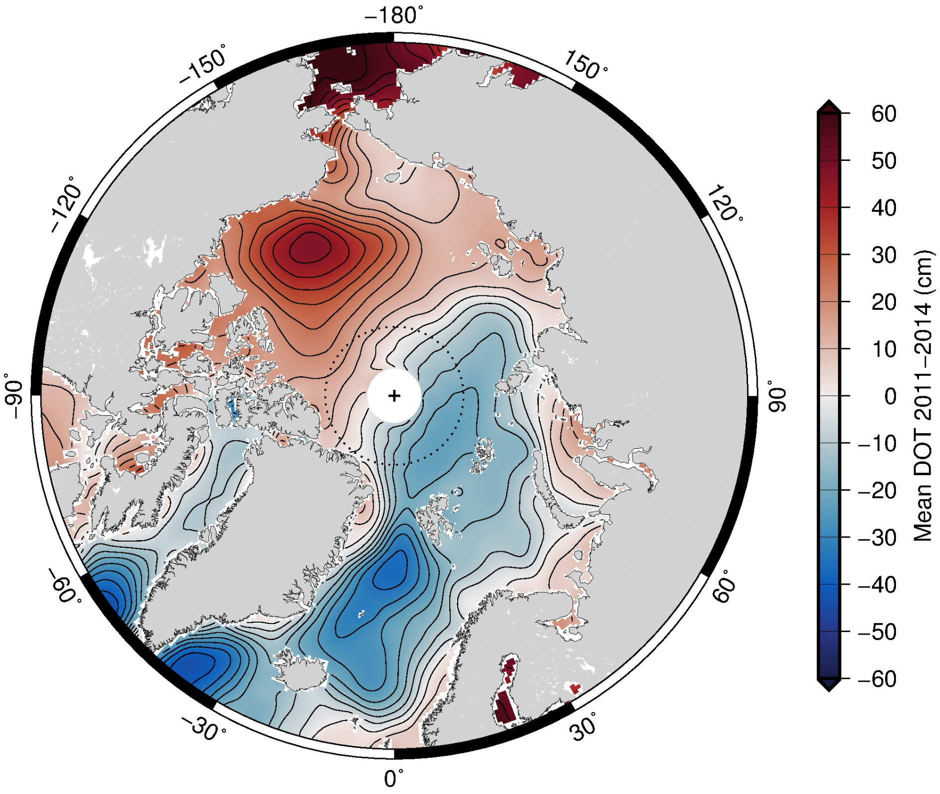

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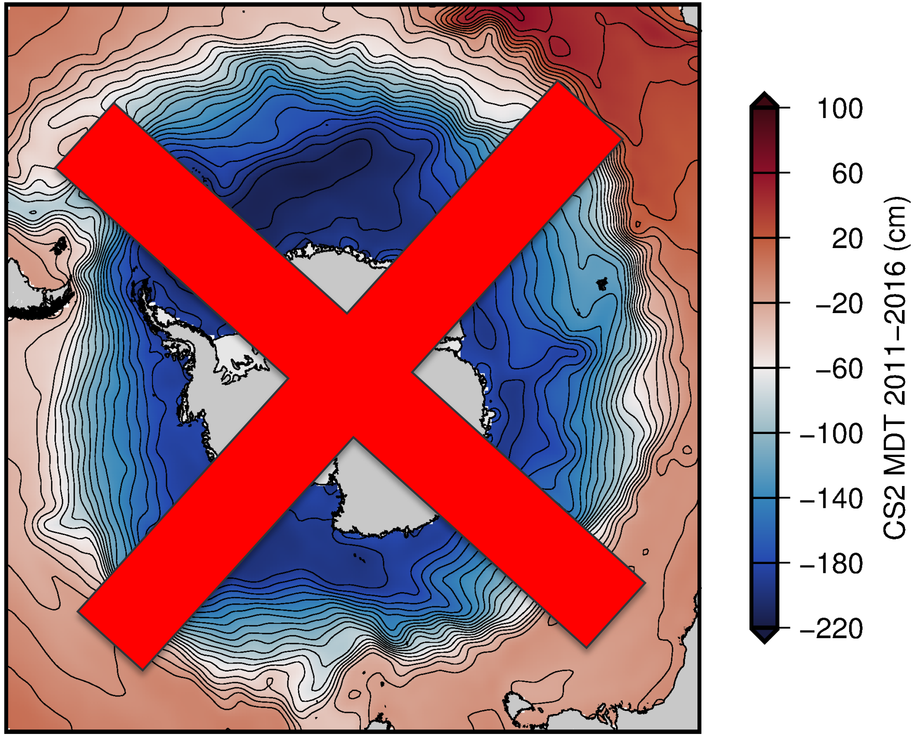

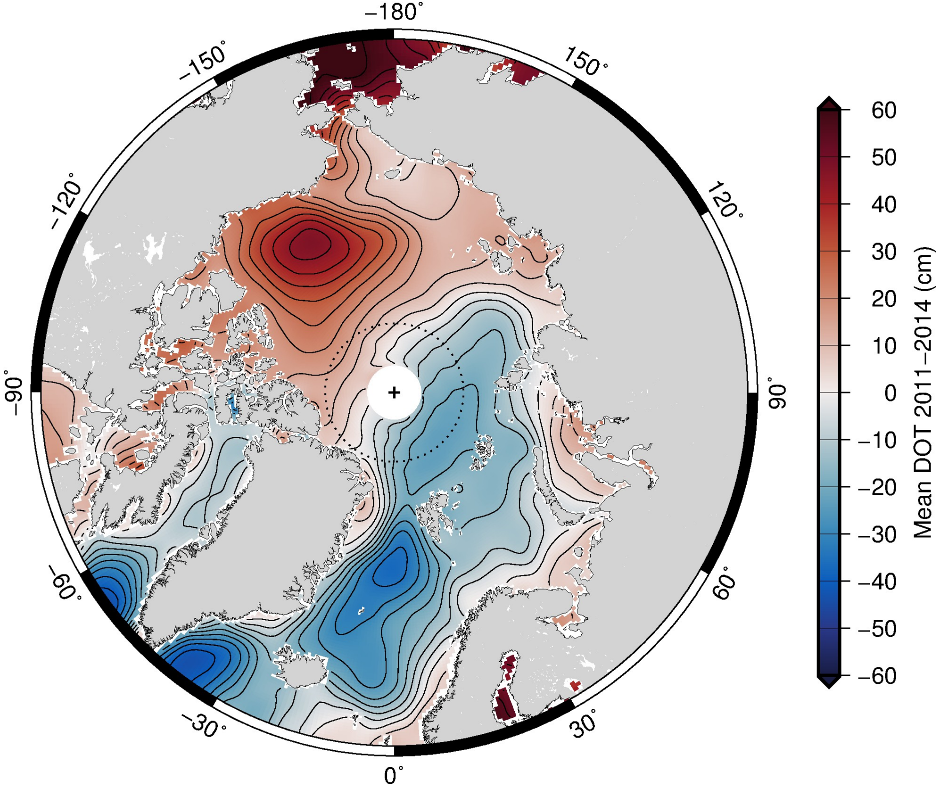

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- Arctic sea has cover has been changing rapidly
- What’s been happening in the ocean?

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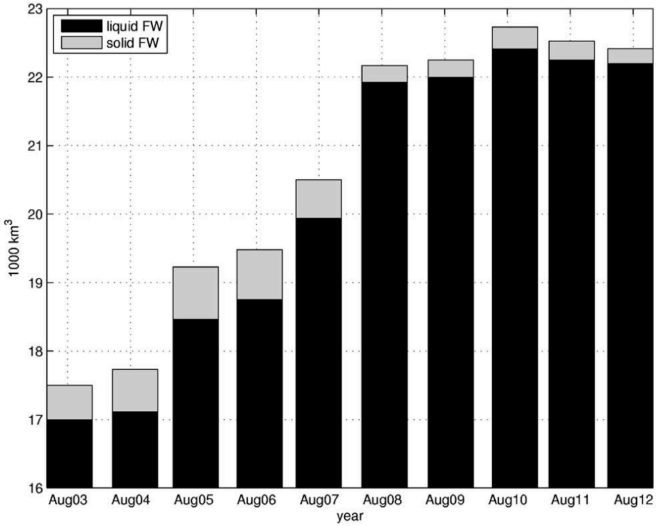

Krishfield et al. (2014), *JGR-Oceans*

- Arctic sea has cover has been changing rapidly
- What's been happening in the ocean?
  - Beaufort Gyre freshwater content increase

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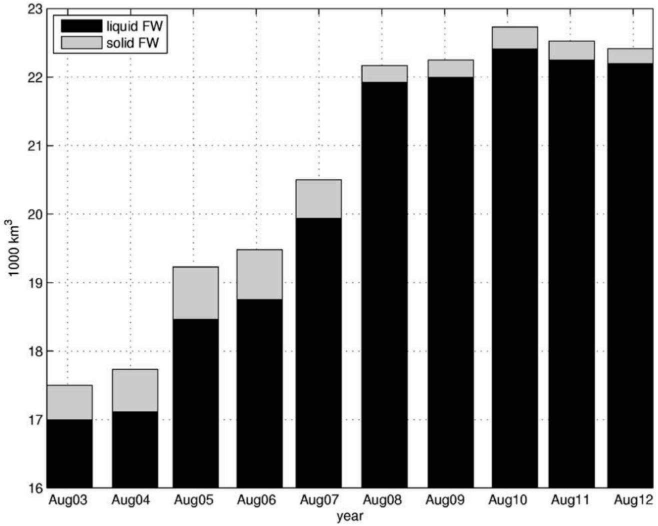

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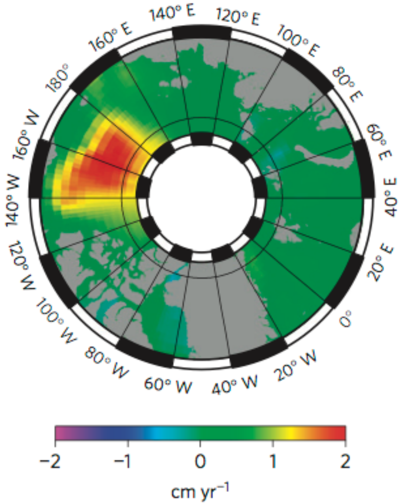

Giles et al. (2012), *Nature Geoscience*

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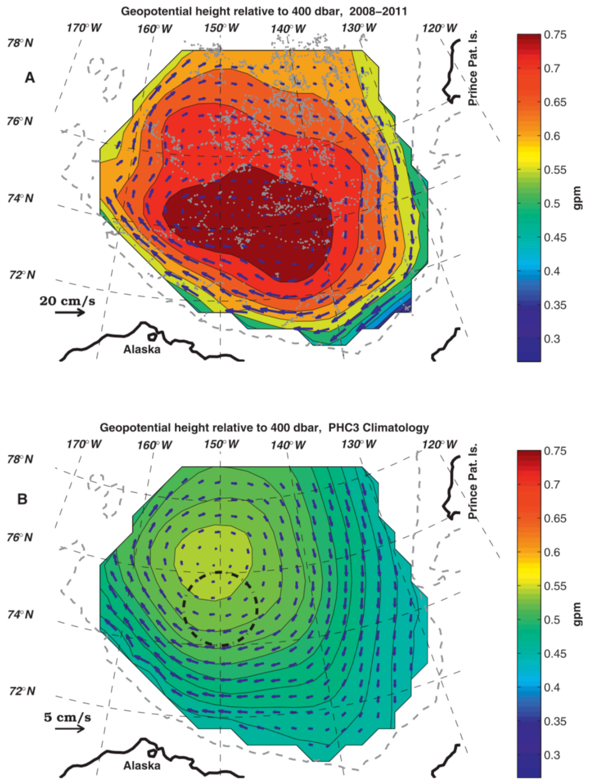
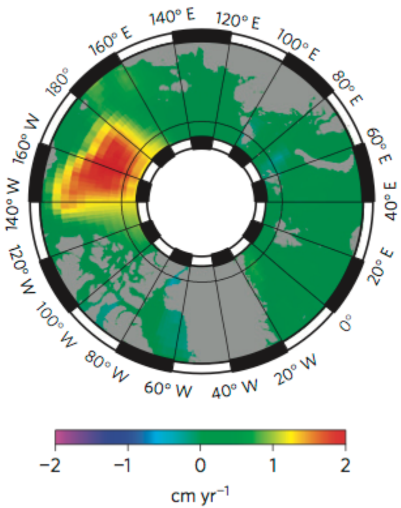


McPhee et al. (2013), *J. Climate*



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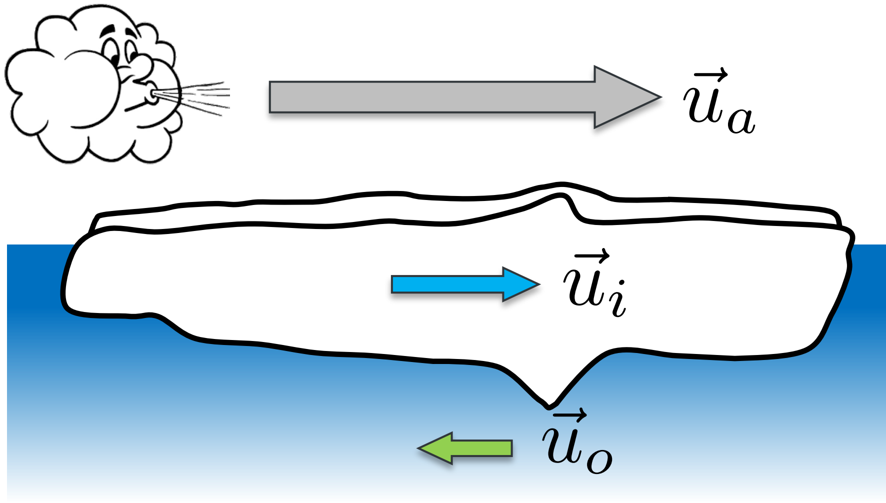
- Arctic sea has cover has been changing rapidly
- What's been happening in the ocean?
  - Beaufort Gyre freshwater content increase
  - Increase in sea level
  - Speed up of surface currents

2. Surface stresses

- Changes indicate surface stress increase/changes
  - Cannot be explained by atmospheric circulation change
- Very few observations of upper ocean to investigate this
- Currents often ignored in ice-ocean stress calculations

$$\vec{\tau}_{io} = \rho C_d(\vec{u}_i - \vec{u}_o)|\vec{u}_i - \vec{u}_o|$$



- New monthly sea level record gives us <u>monthly surface currents</u>
- Currents are similar magnitude to drift (sometimes faster!)

2. Surface stresses

- Can calculate sea ice-ocean stress and see the effect of non-zero upper ocean currents:

$$\vec{\tau}_o = (1-C)\underbrace{\vec{\tau}_{ao}} + C\underbrace{\vec{\tau}_{io}}$$

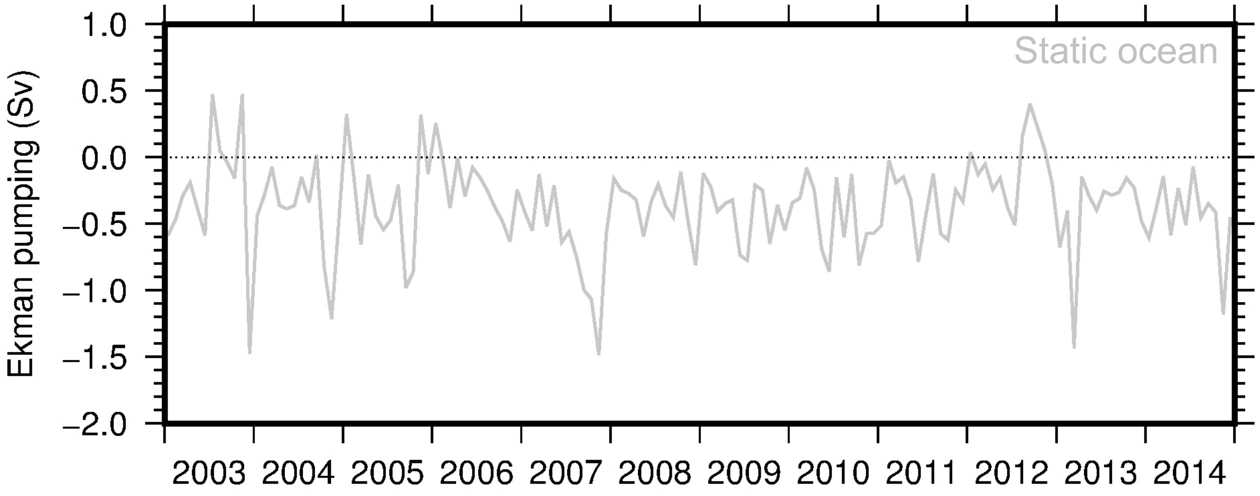
$$\vec{\tau}_{ao} = \rho C_{da}\vec{u}_a|\vec{u}_a|$$

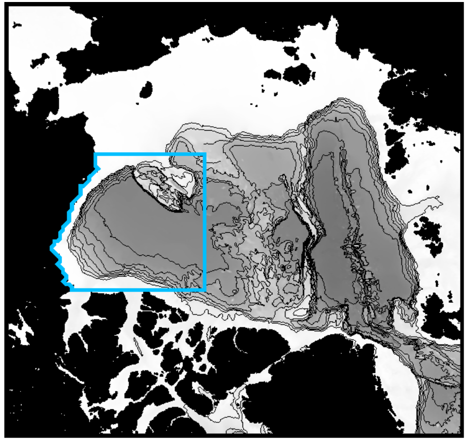
$$\vec{\tau}_{io} = \rho C_{do}(\vec{u}_i - \vec{u}_o)|\vec{u}_i - \vec{u}_o|$$

- Ekman pumping (downwelling): $w_E = \dfrac{1}{\rho f}(\nabla \times \vec{\tau}_o)$

3. Atmosphere–ice–ocean momentum transfer

- Beaufort Gyre Ekman pumping with static ocean – nearly always negative

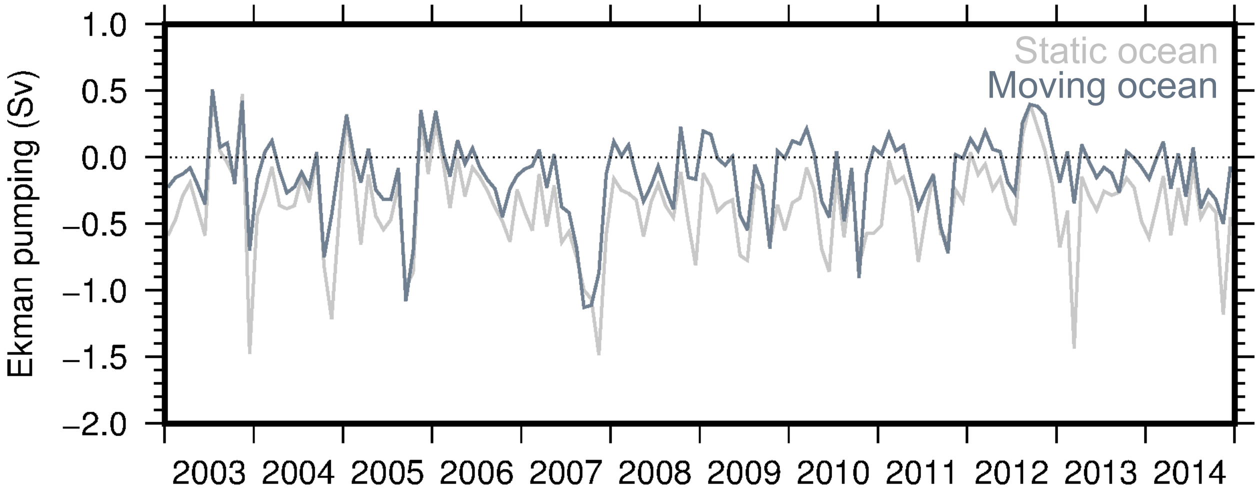


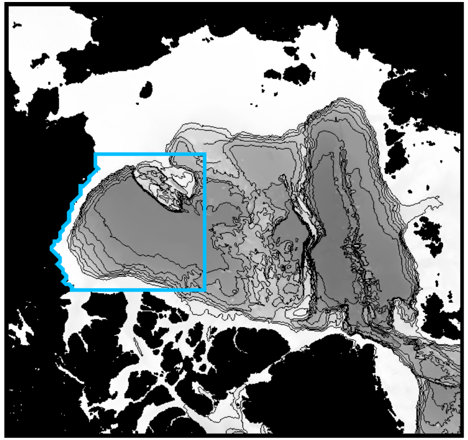


Meneghello et al. (2017); Dewey et al., (2018); Zhong et al. (2018)

3. Atmosphere–ice–ocean momentum transfer

- Beaufort Gyre Ekman pumping with static ocean – nearly always negative
- Including ocean current reduces Ekman pumping by nearly two thirds!
  - Always positive during the winter, means static ice, ocean drag induces upwelling





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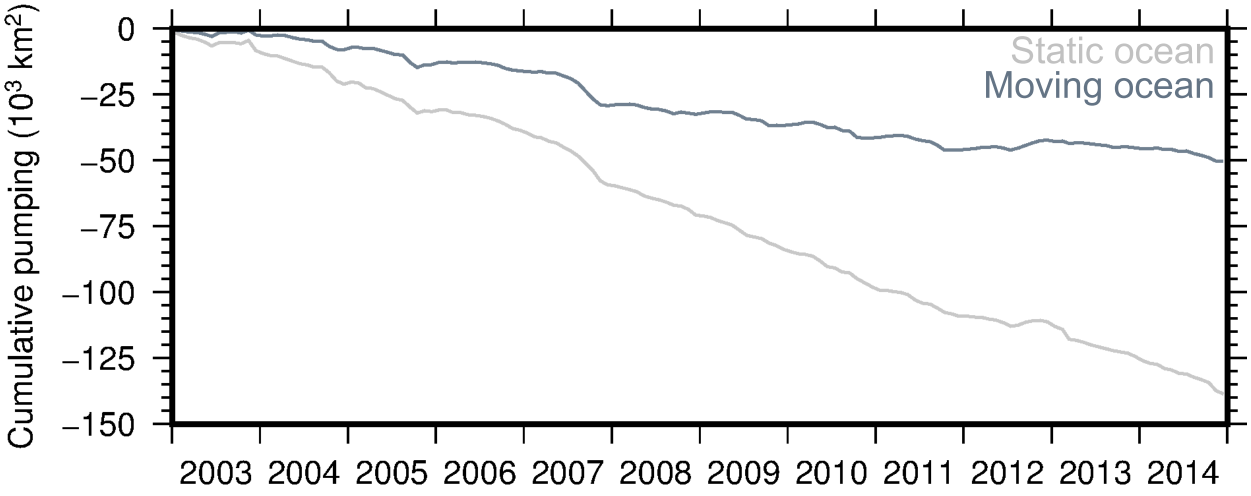

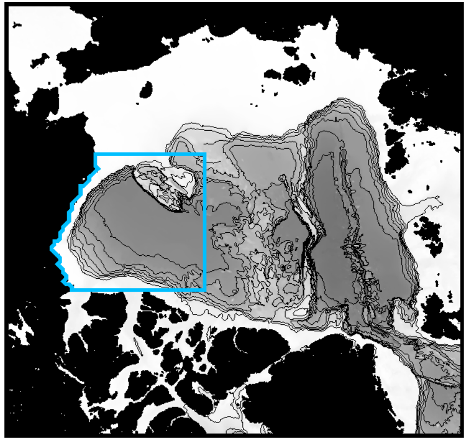

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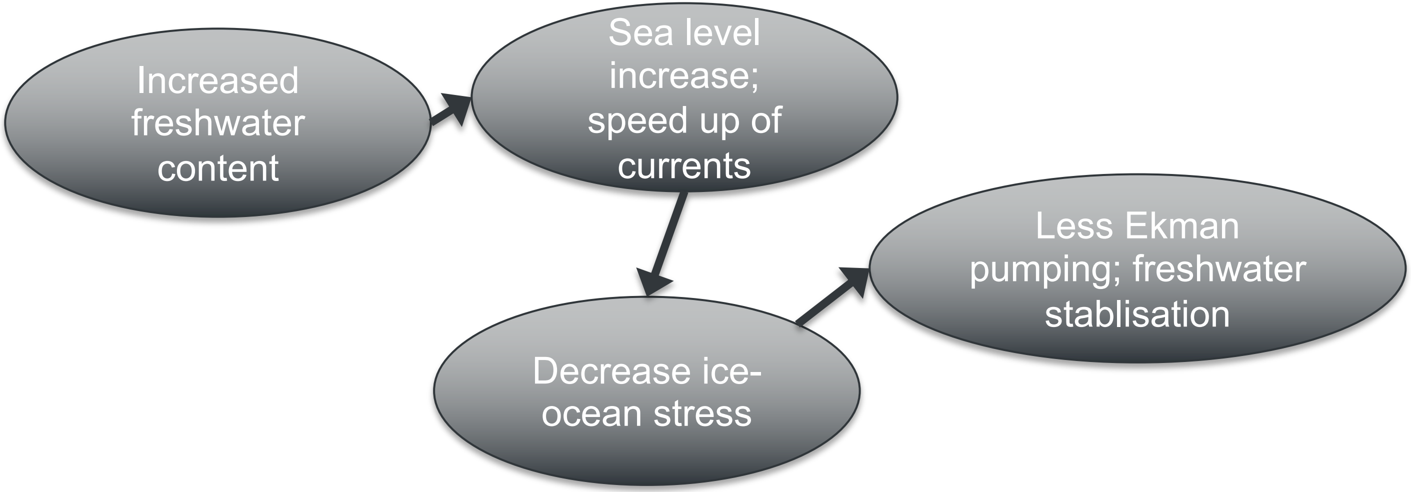

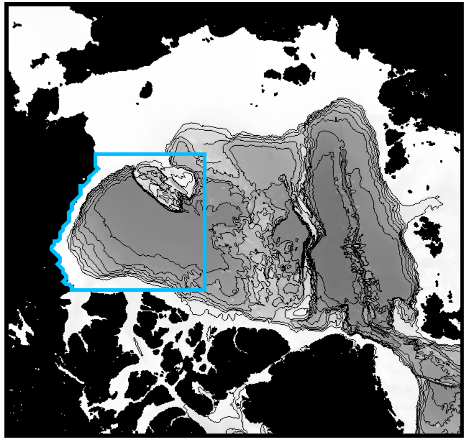

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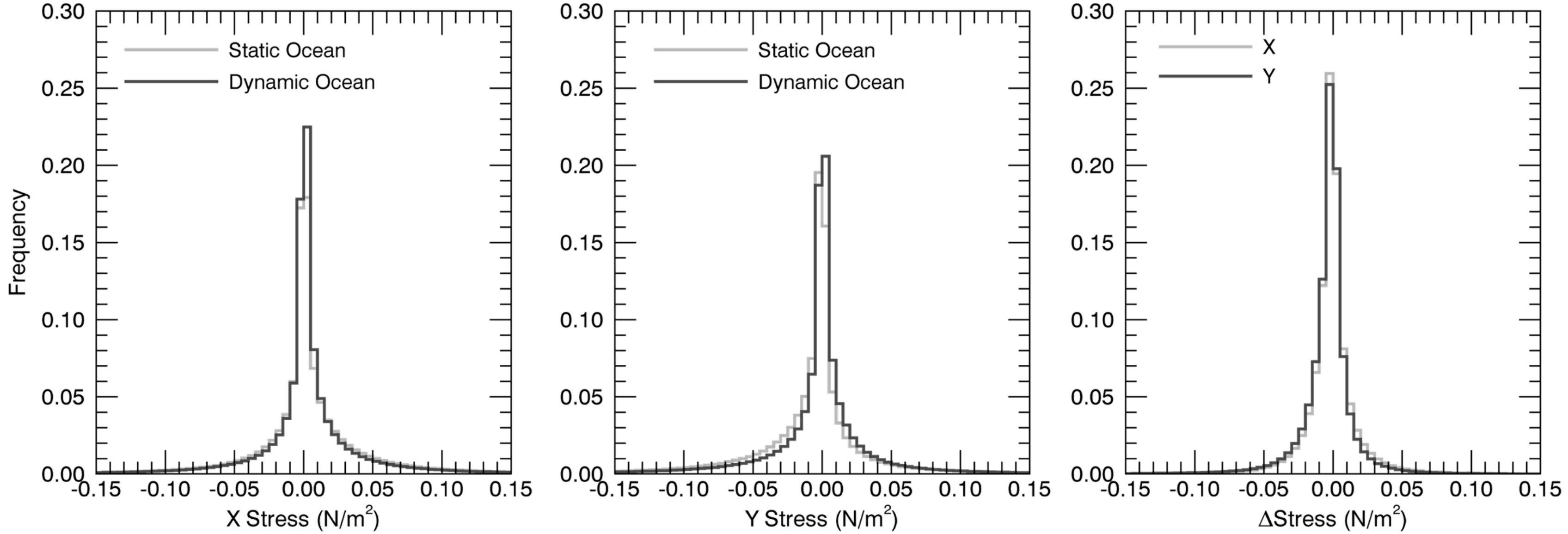
3. Atmosphere–ice–ocean momentum transfer

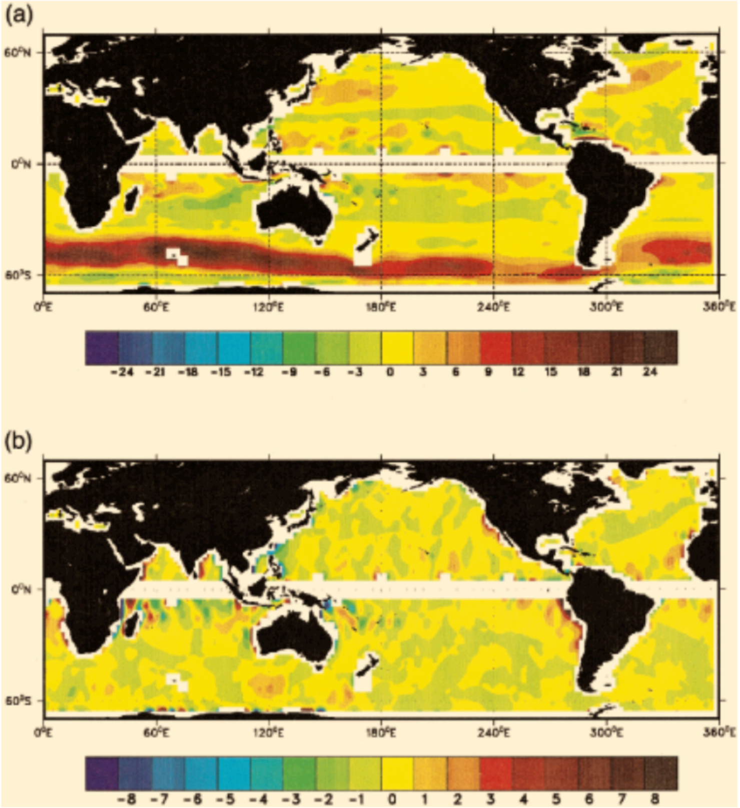
- Also important for the sea ice momentum budget
  - Significant difference in direction
  - Difference when including dynamic ocean is similar magnitude to absolute stress



4. Atmosphere–ice–ocean energy transfer

- Can also calculate work done on ocean geostrophic currents

$$W = \vec{\tau}_o \cdot \vec{u}_g$$



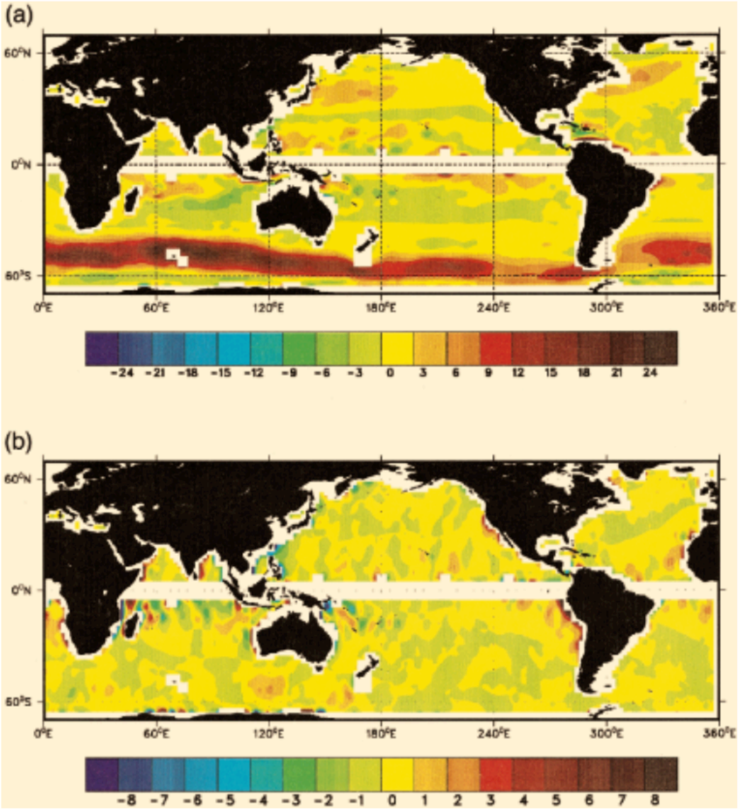
Wunsch (1998), *J. Physical Oceanography*

4. Atmosphere–ice–ocean energy transfer

- Can also calculate work done on ocean geostrophic currents

$$W = \vec{\tau}_o \cdot \vec{u}_g$$

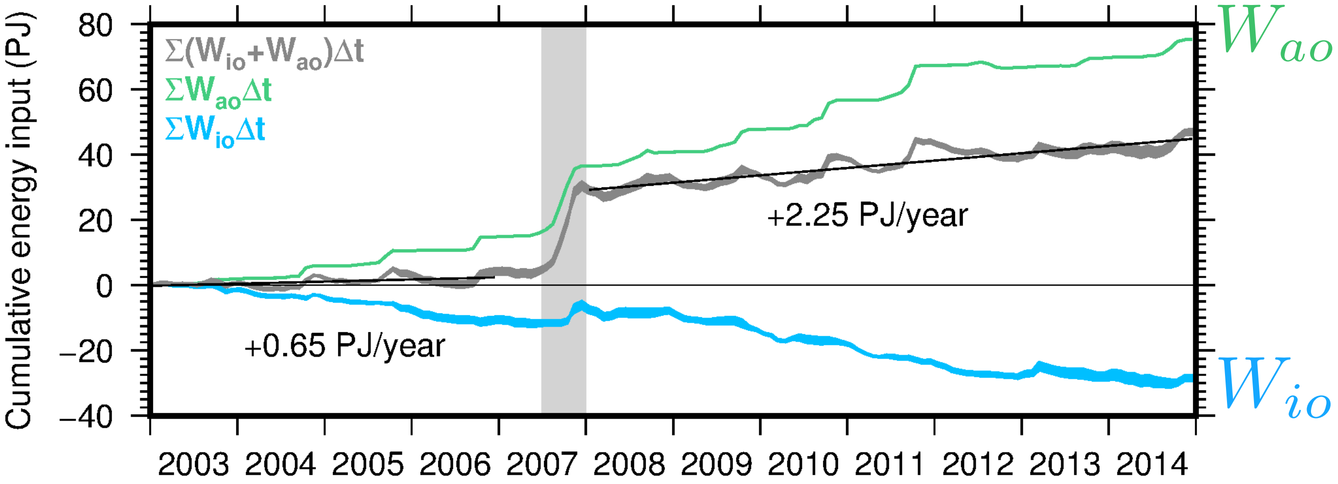
$$W = \underbrace{(1 - C)\vec{\tau}_{ao} \cdot \vec{u}_g}_{W_{ao}} + \underbrace{C\vec{\tau}_{io} \cdot \vec{u}_g}_{W_{io}}$$



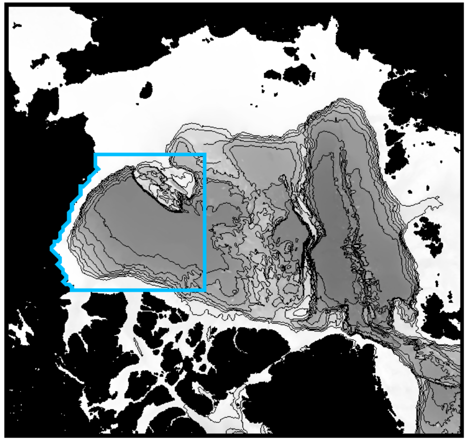
Wunsch (1998), *J. Physical Oceanography*

4. Atmosphere–ice–ocean energy transfer

- Energy input dominated by direct from atmosphere
- Sea ice almost always acts to dissipate energy on average
- Major change in 2007 – huge energy input and sustained increases after



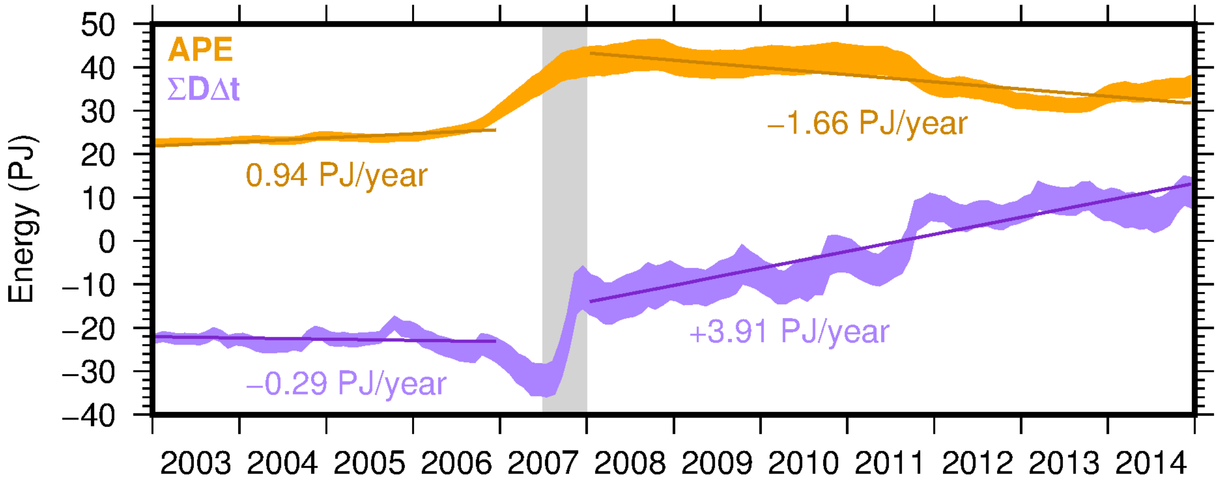
Armitage et al., *in review*



Wunsch (1998), *J. Physical Oceanography*

4. Atmosphere–ice–ocean energy transfer

- Look at other terms in mechanical energy balance
- Find increased available potential energy
- Implies increased dissipation (by eddies) or advection out of the gyre



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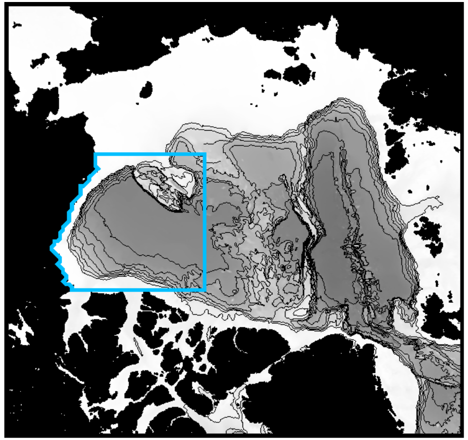


Wunsch (1998), *J. Physical Oceanography*

5. Eddy–ice interactions

- Sea ice momentum equation:

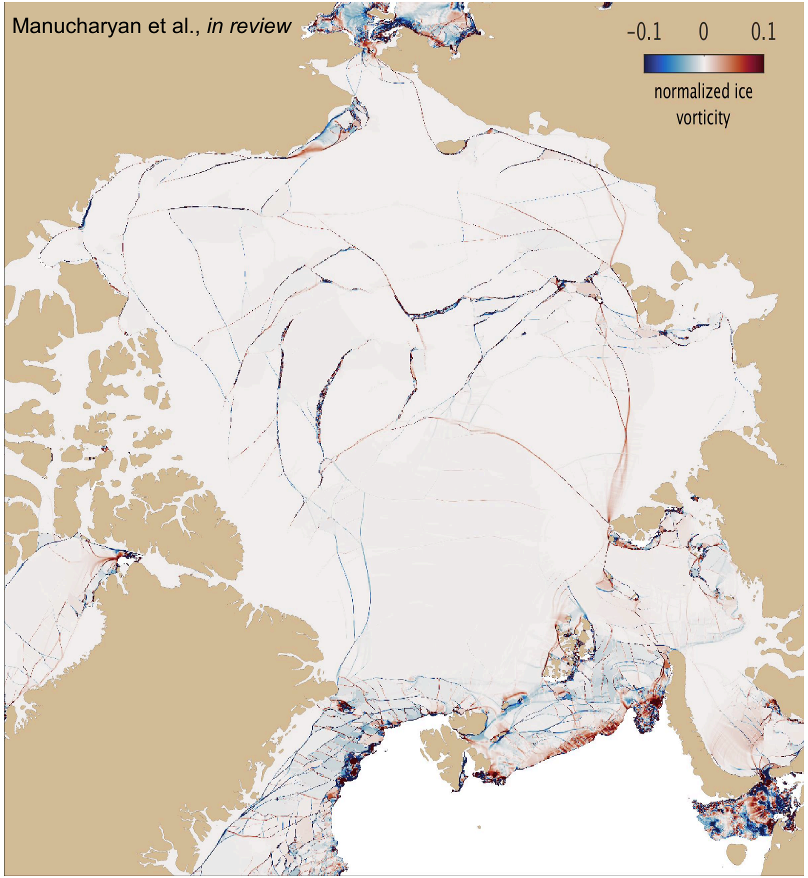
$$m\frac{\mathrm{D}\vec{u}_i}{\mathrm{D}t} = \vec{\tau}_{ai} + \vec{\tau}_{io} - mf(\vec{k} \times \vec{u}_i) - mg\nabla\eta + \nabla \cdot \sigma$$

- In MIZ conditions, summer conditions, *m* (i.e., thickness, concentration) gets small, ice (internal stress) gets weaker
- Get to the limit where ice-ocean stress, Coriolis, and internal stress are similar magnitude
- Find that ice motion is heavily influenced by mesoscale ocean eddies

Manucharyan et al., *in review*

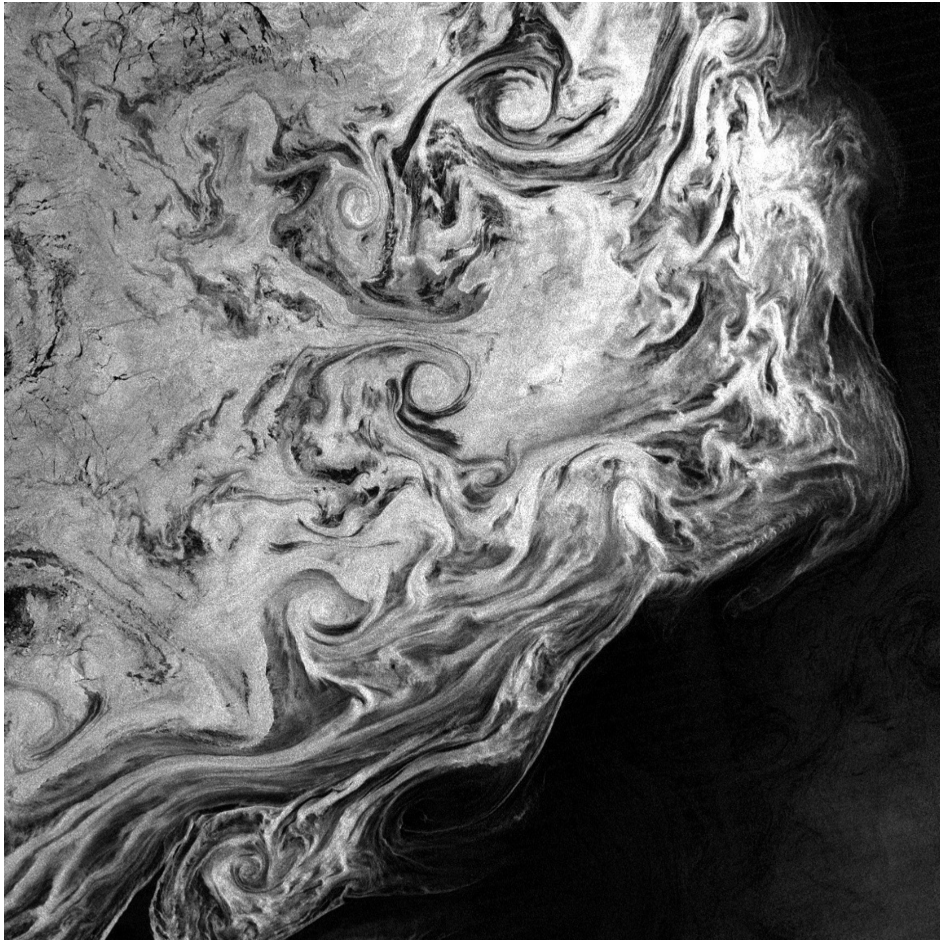
5. Eddy–ice interactions

- Animation shows high-res ice *vorticity* from ECCO
- Starts at end of winter
  - Thick, consolidated, strong ice
- Transitions into summer
  - Thinner, weaker, dispersed ice
- See clearly the impact of ocean eddies during summer



5. Eddy–ice interactions

- Sentinel-1a/b provide ~daily coverage of the central Arctic Ocean
- Provide high-resolution (~10km) ice kinematics
- Eddy-ice motions clearly visible in MIZ
- Preliminary evidence of eddy-ice motions in summertime
  - Need to quantify uncertainty
  - Noisy in summer



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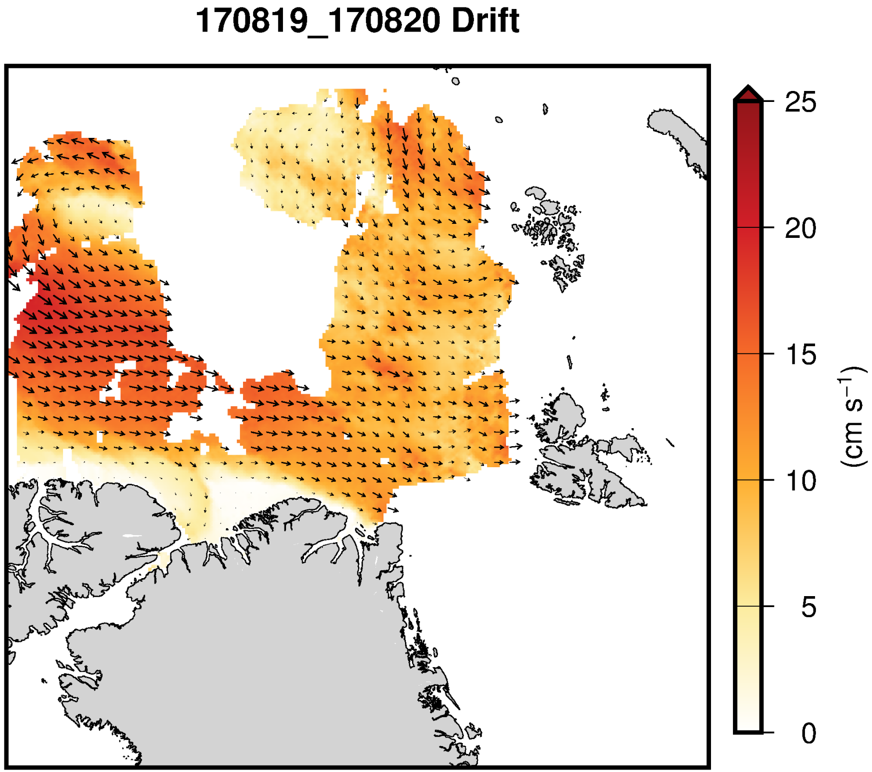

Armitage et al., *in prep*

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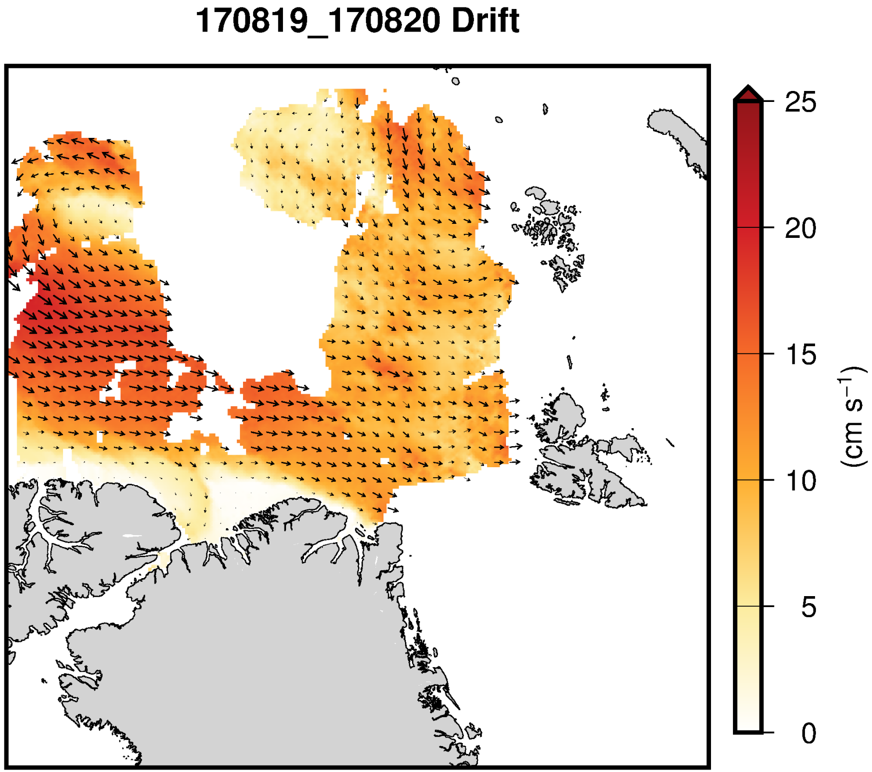

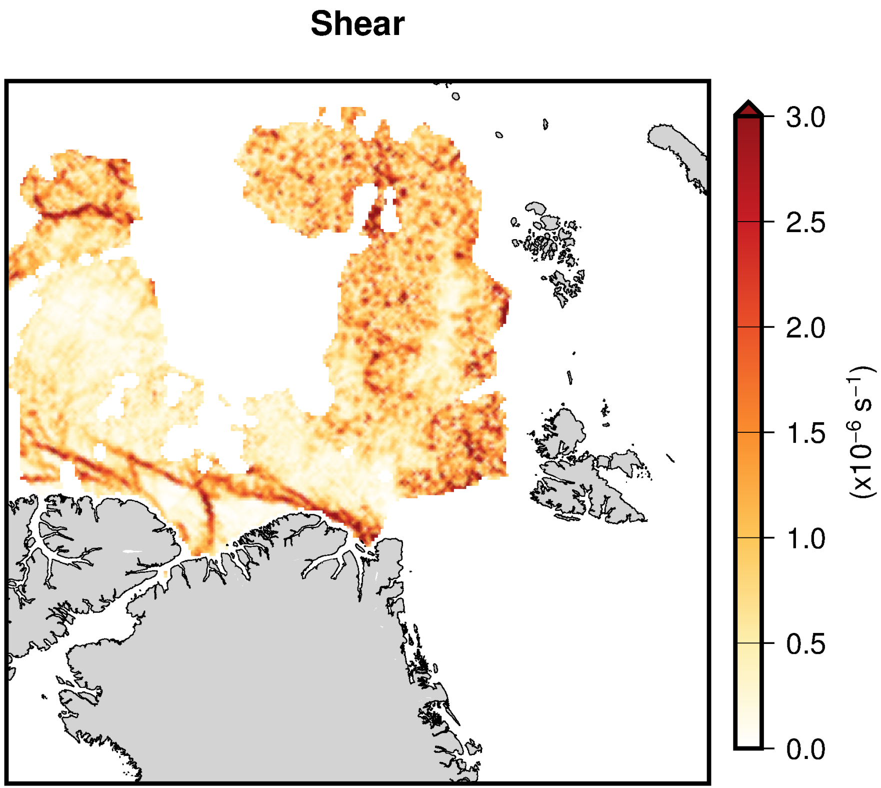

Armitage et al., *in prep*

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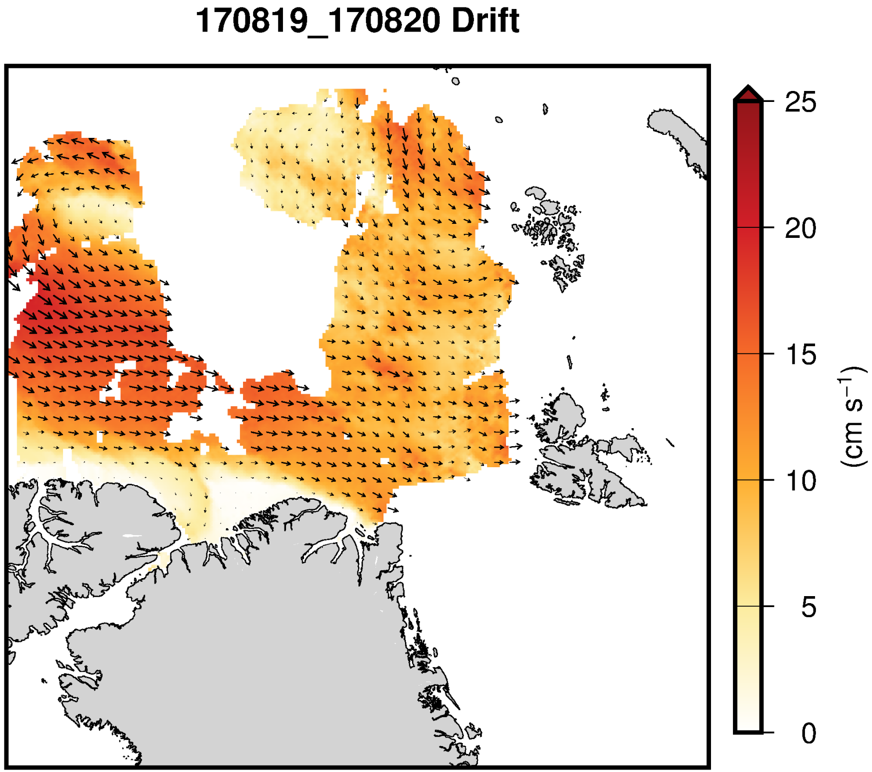

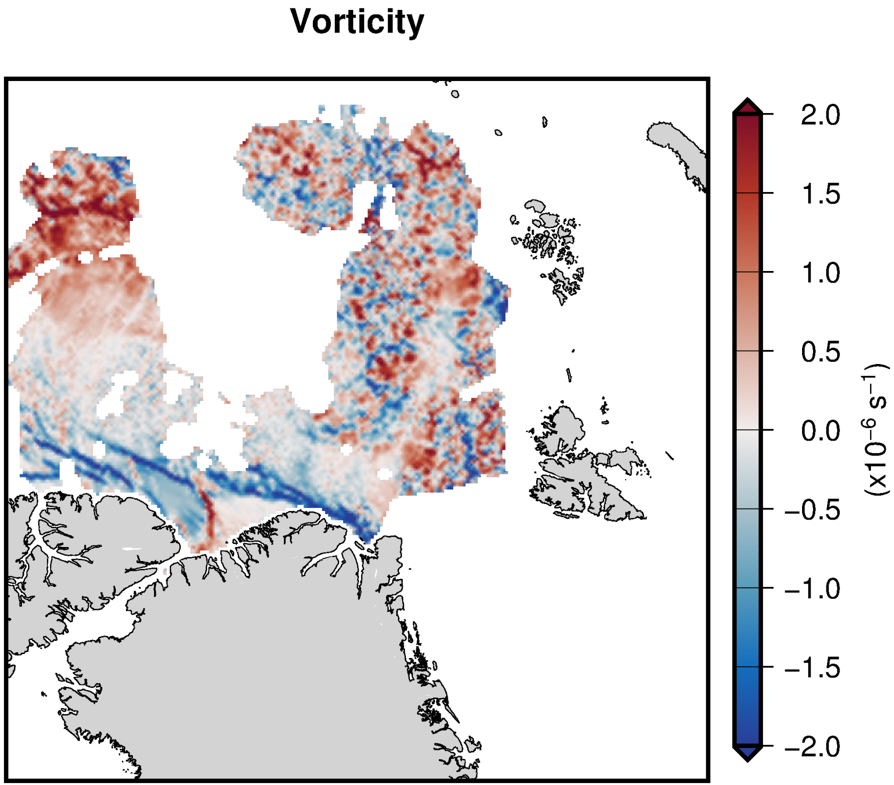

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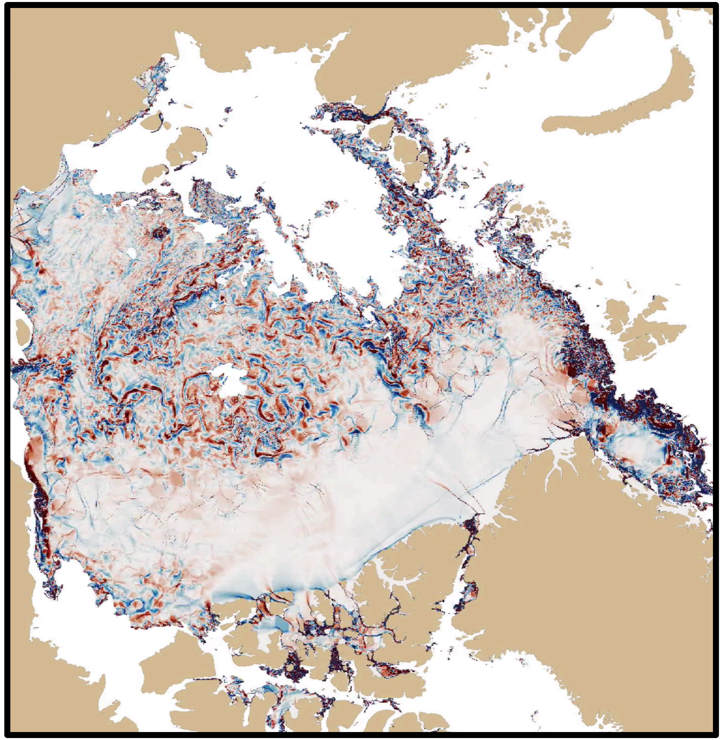

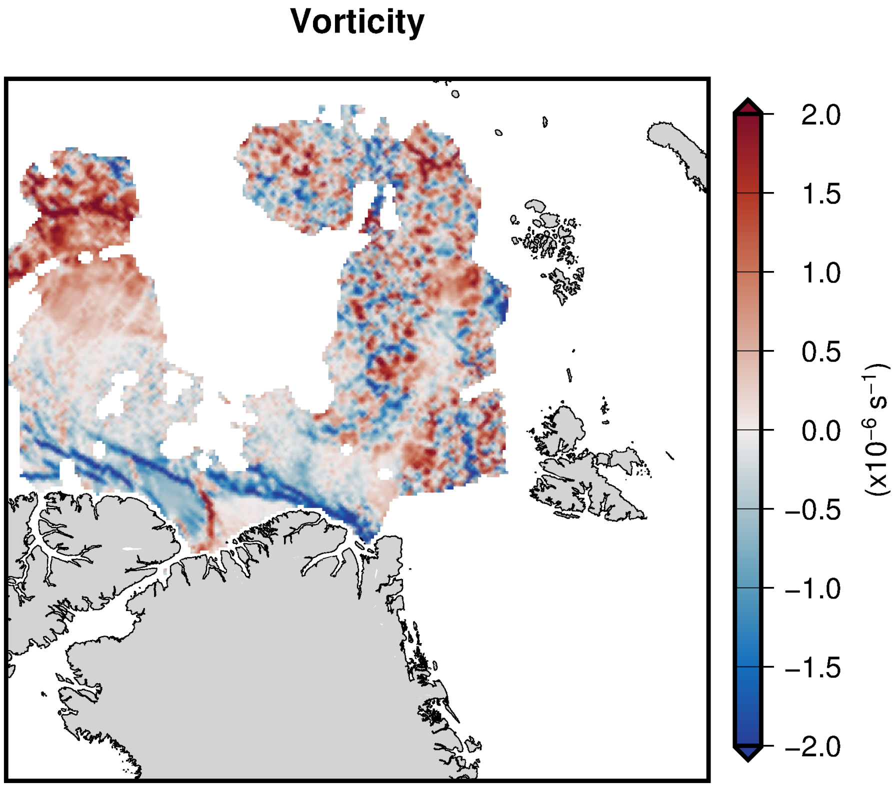

Summary

- Accounting for upper ocean currents significantly changes ice-ocean stress estimates
- Ekman pumping is reduced ~two thirds when ocean currents included
  - Increased current act to modulate Ekman pumping, stabilize freshwater content
- Direct atmosphere-ocean work dominates energy input to the gyre; sea ice generally dissipates energy
  - Loss of sea ice mean more energy input, more eddies, more mixing
- Evidence for strong eddy-ice interactions in MIZ and during summer

Upper ocean currents are super important for ice-ocean interactions and need to be accounted for!

Data: Arctic Ocean: http://www.cpom.ucl.ac.uk/dynamic_topography/

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